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## Can Li-rich K giants eject shells? Assembling the lithium puzzle in K giants

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**Abstract.** The existence of K giant stars with high Li abundance continues to challenge the standard theory of stellar evolution. All recent extensive surveys in the Galaxy show the same result: about 1% of the mainly normal slow rotating K giants are Li rich. We explore here a model with two scenarios based on the important relation of Li-rich and Li-poor K giants with IR excesses. In this model, all K giant stars suffer a rapid enrichment and depletion of Li inducing the formation and ejection of circumstellar shells. The observational detection of these shells will not only validate this model, but also will give important hints on the mechanism of Li enrichment of these stars.

### 1. The lithium puzzle

Following the standard stellar evolution theory, Li-rich K giants don't exist. However, they do exist and the failure to completely explain this situation is known in the literature as “the puzzle of lithium-rich K giant stars”. In fact, this fragile element (<sup>7</sup>Li) can survive only in the low temperature surface layers of stars. As the stars evolve in the red giant branch (RGB), the reminiscent main sequence <sup>7</sup>Li abundance is reduced by the action of the first dredge-up. Standard models predict that <sup>7</sup>Li is depleted by a factor of 60 in low mass, solar metallicity stars (Iben 1967). An initial meteoritic Li abundance,  $\log \varepsilon(\text{Li}) \sim 3.2$  (where  $\log \varepsilon(\text{Li}) = \log(N_{\text{Li}}/N_{\text{H}}) + 12.0$ ), will be reduced to about 1.5 in the RGB stars. In reality, RGB stars have been found even more depleted in lithium than this predicted value.

Wallerstein & Sneden (1982) discovered, unexpectedly, the first K giant star with a large Li abundance. After the discovery of some additional Li-rich K giants, a first survey among bright, nearby K giants by Brown et al. (1989), showed that about 1-2 % of K giants were Li rich. At that epoch, nearly 20 Li K giants were already known. During the Pico dos Dias Survey (PDS), based on IRAS sources and intended to discover Post T-Tauri stars, a serendipitous discovery of further  $\sim 20$  new Li K giants was made. These new objects were found among stars of a more distant population and all stars were IRAS sources (Gregório-Hetem et al. 1992; Torres et al. 1995). This discovery established a real connection between Li-rich and Li-poor K giants and far-infrared (FIR) excesses (de la Reza et al. 1996, 1997; Castilho et al. 1995). In general, Li K giants are considered those stars with <sup>7</sup>Li abundances higher than  $\log \varepsilon(\text{Li}) = 1.5$ . Extremely high Li abundances have been found for some giants, as are the cases of IRAS 13539-

4153 with  $\log \varepsilon(\text{Li}) = 4.2$  (Reddy & Lambert 2005), PDS 68 ( $\log \varepsilon(\text{Li}) = 3.9$ , Drake 1998), HD 19745 ( $\log \varepsilon(\text{Li})^{\text{NLTE}} = 4.7$ ,  $\log \varepsilon(\text{Li})^{\text{LTE}} = 4.08$ , de la Reza & da Silva 1995,  $\log \varepsilon(\text{Li})^{\text{LTE}} = 3.90 \pm 0.30$ , Reddy & Lambert 2005). All known Li K giants are found near the RGB bump or near the RGB tip, and even at the giant clump in case of the more massive stars.

Today, up to the year of 2011, various and large surveys in the Galaxy have been made searching for new Li K giants. In Table 1 all these surveys are described. The results of these surveys are important because different regions of the Galaxy as the thin and thick disks and the bulge were explored. Also, these surveys covered giant stars of different metallicities (solar and metal deficient) and of different stellar masses.

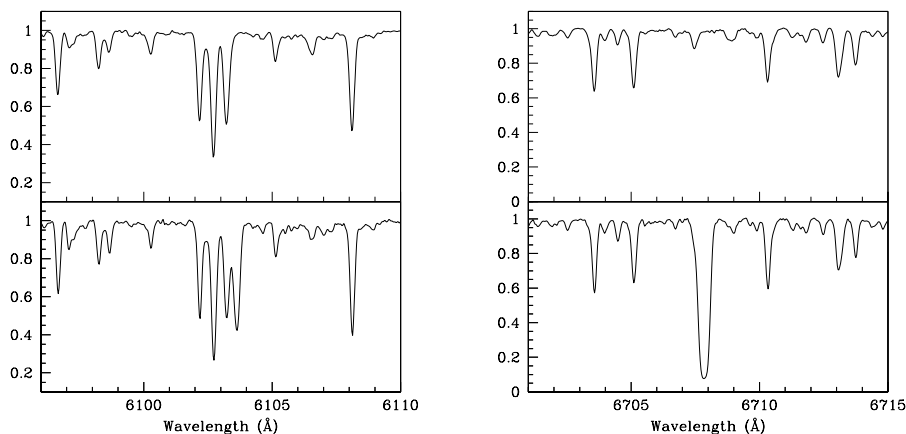


Figure 1. Example of the spectra of normal Li-poor giant and Li-rich K giant in the regions of the Li I lines at 6104 Å and 6708 Å. *Upper panel* - normal K giant, *bottom panel* - Li-rich K giant.

In all these cases, and quite surprisingly in a certain way, the rate of Li K giants is always around 1 %. There is, however, a noticeable exception: among the less numerous fast rotating K giants (with  $v \sin i \geq 8 \text{ km s}^{-1}$ ) the rate of Li K giants increases to  $\sim 50 \%$  ! (Drake et al. 2002). We must note that in this case almost all of these fast rotating stars presented FIR excesses. We can conclude that the main surveys described in Table 1 with a rate of Li K giants of about 1% represent more the normal, slow rotating ( $v \sin i < 8 \text{ km s}^{-1}$ ) K giants population. It is important to note that the Li-rich and Li-poor K giants have the same general stellar properties, being the  $^7\text{Li}$  abundance the sole difference. This can be seen, for instance, in the spectra of both, Li-poor and Li-rich, K giants shown in Figure 1.

## 2. The lithium enrichment models

Some tentative models were published trying to explain the Li K giant phenomena. Some of these models invoke pure external, other pure internal causes or a mixture of both. Those with external ones propose that the giant star has engulfed a planet or a brown dwarf. This could explain, in principle, the increasing Li abundance in the star resulting from the swallowing an external object and explaining at the same time an increase of the stellar rotation by transfer of momentum (Alexander 1967; Siess &

Table 1. Surveys for Li-rich K giants

Candidates	Properties	Li giants	Rate	References
670	Nearby objects	10	1.5 %	Brown et al. (1989)
	IRAS (distant objects)	19		de la Reza et al. (1997)
280	Selected IRAS	5	1.7 %	Castilho et al. (1998)
	High rotating giants		50 %	Drake et al. (2002)
400	Galactic Bulge	2	0.5 %	Gonzalez et al. (2009)
401	Galactic Bulge	3	0.7 %	Lebzelter et al. (2011)
824	Galactic thick disk	6	0.7 %	Monaco et al. (2011)
2000	Extended survey	19	1.0 %	Kumar et al. (2011)
700	Metal poor	6	0.8 %	Ruchti et al. (2011)

Livio 1999). The pure internal model (Palacios et al. 2001) is based on an extra mixing parameter, also known as a diffusion coefficient  $D_{\text{mix}}$ . A canonical value of  $D_{\text{mix}}$  does not conduce to the production of extra  $^7\text{Li}$  which requires an increase of  $D_{\text{mix}}$  by a factor of 100. However, the increasing of  $D_{\text{mix}}$  is for the moment an *ad-hoc* hypothesis and the mechanism needs a self-consistent treatment. Denissenkov & Weiss (2000) and Denissenkov & Herwig (2004) proposed a mixed scenario in which the engulfment of a planet provokes the required increase of  $D_{\text{mix}}$  producing the extra-mixing and leading to the increase of  $^7\text{Li}$  in the stellar atmosphere. Note that following these authors a tidal effect in a binary star could also produce this effect.

Nevertheless, the “engulfing” models, pure or mixed, have severe problems due to the following considerations: *a)* these models may be applied mainly to rapid rotating giants while the majority of Li-rich giants are slow rotators; *b)* the engulfing process can happen everywhere in the RGB and this is not observed, because Li K giants are concentrated mostly close to the RGB bump; *c)* finally, enrichment with the element  $^9\text{Be}$  is expected together with  $^7\text{Li}$  in the planet engulfing scenario which is not observed in the Li K giants (Melo et al. 2005).

In the “Lithium flash” model proposed by Palacios et al. (2001), a thermal instability causes the  $^7\text{Li}$  flash increasing the Li abundance with a duration of  $\sim 10^4$  yr. This produces an increase of the stellar luminosity thus explaining the mass loss. We also note that a rapidly rotating single G8 II giant, with high Li abundance and a magnetic field, have been detected by Lèbre et al. (2009). As far as we know, this is the only giant known with these properties.

### 3. The lithium – mass loss scenario

We proposed (de la Reza et al. 1996, 1997) a model with the aim to interpret the “high Li abundance – FIR excess” relation. Here, all K giants pass by a rapid internal enrichment of the atmosphere by new  $^7\text{Li}$  following, probably, the known “ $^7\text{Be}$  mechanism”. This powerful event produces the formation of a spherical circumstellar shell, which is subsequently detached from the star. This happens at the RGB bump or between the bump and the tip in the RGB, where the majority of Li K giants is found. The ejected shell moves away from the star with constant (and slow) velocity. Depending on the duration of the process of shell formation, we obtain two relatively different scenarios. In the first one, as described in de la Reza et al. (1996, 1997), the process is very rapid.

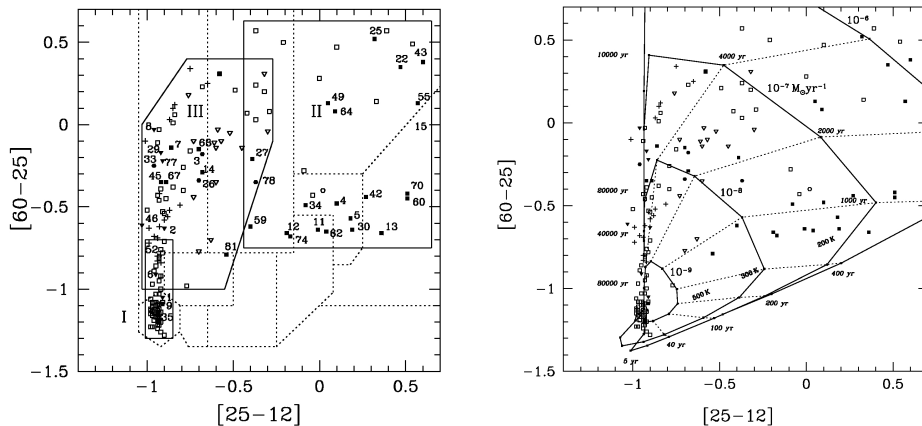


Figure 2. *Left (a)*: Distribution of IRAS sources corresponding to K giants contained in three regions labeled I, II, and III. The regions marked by broken lines are those defined by van der Veen & Habing (1988). Labeled filled symbols correspond to Li-strong K giants: *squares* (three fluxes are of good quality), *triangles* (one flux is only an upper limit), and *hexagons* (two fluxes are only upper limits). Corresponding open symbols represent Li-weak K giants. *Right (b)*: Same points are presented together with evolution curves of CS. The four curves calculated for an CS expansion velocity of  $2 \text{ km s}^{-1}$ , star temperatures and radii equal to  $4000 \text{ K}$  and  $20 R_{\odot}$  respectively, correspond to mass losses between  $10^{-9}$  and  $10^{-6} M_{\odot} \text{yr}^{-1}$ . The time steps are also indicated. (Figure taken from de la Reza et al. 1997.)

Consider the FIR diagram based on IRAS 12, 25 and  $60 \mu\text{m}$  colors presented in Figures 2a and 2b. Here the star begins its sudden Li enrichment in the box I (at the left bottom part of the figure) where the giants present no FIR excesses. The formed shell is rapidly ejected with the velocity  $V = R/t$ , where  $t$  is the time and  $R$  is the distance of the shell to the star. The path of the detached shells in the IRAS color-color diagram forms a loop (see Figure 2b) returning after to the same initial box. The size of the loops depends on the considered mass loss and for values of  $V$ , of the order of  $1$  to  $2 \text{ km s}^{-1}$ , the complete loop is realized in  $\sim 100\,000 \text{ yr}$ . The positions of the different Li-rich giants (black squares) or Li-poor giants (open squares) describe, in this scenario, the present evolutionary stage of the shell. It is proposed in this scenario that the Li-poor giants, with or without FIR excesses, rapidly deplete the new Li. For this scenario, all shells are detached.

In de la Reza et al. (1996, 1997) no mention is made about the mechanism of Li enrichment. Probably, the most interesting model to be considered for this case is “The lithium flash: thermal instabilities generated by lithium burning in RGB stars” as proposed by Palacios et al. (2001). In any case, the first scenario of de la Reza et al. (1996, 1997) has the disadvantage of requiring an extremely rapid, almost explosive,  $^7\text{Li}$  enrichment phenomenon. Also, there is no way of predicting the size of the shell.

The second scenario, equally physically compatible with the shell evolution as presented in the Figure 2b, can be presented. Here, the  $^7\text{Li}$  enrichment mechanism is slower than in the first scenario and could last some few thousand years. As before, the giant star begins its enrichment in the same, non-FIR excess, box mentioned above, but differently, an attached, gradually increasing, shell is formed, with the same velocity

$V = R/t$ ,  $R$  being the size of the increasing shell. This shell formation lasts up to the moment when the star ceases to be Li enriched, then the shell is detached and continues to expand with the same velocity,  $R$  being now the size of the shell plus the distance to the star. Contrary to the first scenario, the size of the shell can be estimated and perhaps we are in a more plausible physical situation, not requiring an explosive Li enrichment process. In this scenario it is expected that all Li-rich K giants in the IRAS diagram have non-detached shells, whereas the shells are detached in the case of the Li-poor giants.

#### 4. Conclusions

We presented here a general picture of what is called in the literature “the Li puzzle of K giant stars”. The complete collection of Galactic surveys for new Li-rich giants until 2011, presents the same impressive result indicating that about 1 % of the giants are Li-rich stars. Being these Li K giants similar, in all their general stellar properties, to the Li-poor K giants, it is much probable that the Li-rich state results from a short episode of Li enrichment during the evolutionary life of all K giants in the RGB. An important exception to the frequency of Li-rich stars among K giants was found for the less numerous fast rotating ( $v \sin i \geq 8 \text{ km s}^{-1}$ ) K giants, where about 50 % are Li rich (Drake et al. 2002). In this case, a fast rotating K giant, after gaining its fresh  $^7\text{Li}$ , probably prevents the  $^7\text{Li}$  to be depleted by the action of the stellar rotation. We note that an important step in the study of the properties of Li-rich and Li-poor giants was the discovery of their strong relation with FIR (IRAS) excesses.

We have outlined here two scenarios, related to the fast Li enrichment, depletion and mass loss, presented originally in de la Reza et al. (1996, 1997). In one scenario, the very fast  $^7\text{Li}$  enrichment is followed by the detachment of a circumstellar shell. In the second scenario, practically the same processes occur, but much more slowly. Here the giant star becoming Li rich, develops a progressively extended attached shell. Only when the internal  $^7\text{Li}$  enrichment ceases and the new  $^7\text{Li}$  is depleted, the shell is detached. On the other hand, we should mention that Pereyra et al. (2006) has performed polarimetric measurements of Li K giants. They show the existence of a correlation between the intrinsic polarization and the IRAS 25  $\mu\text{m}$  flux, suggesting that dust scattering is the source of polarization and indicating the existence of non-symmetrical shells.

We believe that it will be very important to visualize these shells by imaging. Whether they will be detached or non-detached, will confirm one of the “Li – mass loss” scenarios and the probably non-spherical appearance of the shells. According to the first scenario all shells must be detached, while in the second one the shells will be attached for Li K giants and detached for Li-poor K giants. In any case, these eventual shells detections will give very important hints to the study of the stellar  $^7\text{Li}$  enrichment. We must not forget that this mechanism represents a clear physical way of how K giants contribute, by means of Li-rich mass loss, to the enrichment of  $^7\text{Li}$  in the interstellar medium of the Galaxy.

#### *Note added in proofs*

A recent important related work appeared in Kirby et al. (2012) (astro.ph/1205.1057, ApJ 752, L16, 2012) referring to the discovery of 14 Li-rich giants among 1764 giants belonging to eight dwarf spheroidal low-metal galaxies, representing a rate of 0.85 %.

These results include the most metal-poor Li-rich known giant ( $\log \varepsilon(\text{Li})^{\text{NLTE}} = 3.15$ ,  $[\text{Fe}/\text{H}] = -2.82$ ). Because the abundance of Li is the only difference among giant stars, these authors “consider the possibility that Li enrichment is a universal phase of evolution that affect all stars, and it seems rare only because it is brief”.

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## 5. Discussion at the Meeting

**A. Miroshnichenko:** It is interesting to hear about this group of Li-rich K-type giants in connection with B[e] objects that were formerly called unclassified and which I call FS CMa stars. About 30 % of CMa stars show Li lines attributed to K-type secondaries. It would be interesting to study the two groups together to reveal possible similarities.

**R. de la Reza:** In fact, some authors as Denissenkov et al. (2004) have proposed that in a binary system, in which one of the members is a Li-rich K giant, a tidal effect induced, in some way, the internal extra mixing required to achieve the Li enrichment in the K-type secondary star.

**T. Rivinius:** What ESO instrumentation/telescopes you can use to observe these shells?

**R. de la Reza:** We can use different possibilities depending on the distances of the targets. Maybe the best results can be obtained using VLTI with their main detectors, in the case of young shells. For the case of older detached shells ALMA could be a solution.